Discussion and conclusions

Discussion, conclusions and future research

Since the mineral composition influences the geophysical properties of rocks, and provides information about their geological evolution, the mapping and analysis of the mineralogy present in a geological outcrop is essential in many field studies. A workflow has been developed to utilize imaging spectrometry with a ground-based instrument setup, to enable the analysis of the mineralogy, lithology or variations in geochemical properties in near-vertical geological outcrops. Close-range hyperspectral imaging provides a non-contact means of analysing mineral abundances, with spatial resolutions in the order of centimetres, and therefore complements multi-scale studies in geosciences. The main outcomes of this project are:

- A scanning setup for ground-based hyperspectral imaging is presented which is practical for geological outcrop analysis.
- A complete workflow was established including data collection, hyperspectral image processing and multitexturing of 3D lidar models with hyperspectral image products.
- The ground-based hyperspectral imagery was photogrammetrically integrated with VOMs derived from TLS data with high accuracy using a cylindrical camera model.
- Two case studies are presented; one in a carbonate system to map limestone and dolomite from weathered surfaces as well as different diagenetic-sedimentary products with very similar chemical and spectral properties at fresh cut quarry walls. In the second case study a siliciclastic system is spectrally analysed to identify carbonate concretions within a shallow marine sandstone succession.

In the following section the main findings of this study are discussed. The section concludes with an outlook and presents a number of issues that requires further research.

HySpex SWIR-320m as a field instrument

Geological outcrops are often situated in remote areas; therefore, for geological field applications, rough and portable instrumentation is required. The HySpex SWIR-320m sensor is an example of a new generation of hyperspectral imager with high spectral performance which is also designed to be rugged, compact and portable. In general, the HySpex instrument has proven its worth under field conditions. As is common for new methods and technologies, some technical modification and improvements can be suggested to support a more efficient data acquirement in the field. For example, in some scan conditions, a horizontal instead of a vertical sensor rotation axis may reduce illumination nonuniformities in an image. To ensure a full coverage of a cliff section multiple scans with low overlap are often required; however, the adjustment of the sensor FOV has been found to be time consuming. An optical view finder could be helpful to adjust the FOV of a scan. Other technical parameters will be improved by ongoing technological progress in the future. The spatial resolution for example is relatively low, with only 320 pixels, but it can be assumed that the spatial resolution will be increased with improved photoelectric chip technology. While the photogrammetric performance of the HySpex SWIR-320m sensor has been empirically evaluated, the assessment of the spectral performance and distortion parameters, such as the smile and keystone effect or the sensor calibration stability, was not the aim of this study.

Close-range panoramic imaging geometry

In contrast to airborne and spaceborne applications, ground-based scanning can be achieved from a non-moving platform. This allows repeated measurements for example to maximize the SNR. Furthermore, no spatial distortions due to platform movement appear. The differences between close-range and nadir hyperspectral scanning are related to the sensor-view geometry and the inherent image geometry. Nadir-images are collected with sensor zenith angle close to zero and show inherent image geometry comparable to planar frame images. The sensor view is always downwards directed at the Earth's surface. In contrast, close-range images are collected with a sensor zenith angle of around 90º, and the sensor-view can be directed upwards (towards the sky) or downwards. Due to the sensor rotation movement, the inherent image geometry of close-range images is not planar. Instead the panoramic images show an angular component in the along-track direction. Both, the sensor-view geometry and the inherent image geometry affect the radiance measurements over an image, resulting in a significant amount of nonuniformities or intensity gradients in the close-range images. The direction of the direct irradiance received by a GS depends on the GS orientation, which is highly variable in rough cliff sections. Furthermore, the diffuse irradiance received by a GS, consisting of scattering from the atmosphere and from the surrounded area, is highly variable in rough and irregular cliff surfaces, due to different exposures to the open sky and to adjacent GSs. Because of the sensor rotation, the sensor-view direction is changing within an image in along-track directions and can result in significant intensity gradients.

Reflectance

In this study, the at-sensor radiance has been transferred into relative reflectance applying EL correction based on two reference spectra obtained from Spectralon calibration panels scanned in the images. The EL correction removes the irradiance and the atmospheric path radiance (path 2 and 4 in Fig 1 of Paper 1). However, diffuse illumination, consisting of atmospheric and adjacency scattering (path 3 and 5 in Fig 1 of Paper 1), a GS has been received, is not subtracted from the at-sensor radiance. Therefore, the obtained quantity does not represent bidirectional reflectance. The diffuse atmospheric irradiance a GS can receive from the upper hemisphere is often significantly restricted due to the close-range scanning geometry. However, the radiance scattered by the GS to the sensor is measured with a small iFOV by the sensor and can be therefore considered as directional. Consequently, the quantity extracted by the EL approach in this study, can best be described as conical-directional reflectance.

The EL correction using Spectralon reflection panels has been found to be an efficient method to extract reflectance values from close-range images. However, a number of restrictions are related to this method. Difficulties for example appear for images in which the calibration panels cannot be placed due to inaccessible terrain, or the image resolution is too low to collect reference spectra from the calibration panels (for long range images). Furthermore, topographic effects are not corrected with the EL approach and, as discussed above, not all scattering effects can be removed by this method.

Spectral processing chain

In this study the ground-based hyperspectral imagery was processed and analysed with methods primarily developed for images acquired from airborne or spaceborne platforms. In general, the assumptions and preconditions related to the spectral classifications and mapping approaches, such as SAM, SFF or MTMF, are also valid and applicable for close-range panoramic images. However, the adoption of the pre-processing methods to remove image nonuniformities and to perform atmospheric and adjacency corrections is critical due to the more complex scan geometry and intrinsic image geometry. Image nonuniformities, such as intensity gradients and bad-pixels, have been observed in all images. Some of these artefacts are common in pushbroom imaging (Schäpfer et al. 2007, Nieke et al. 2008), other nonuniformities seem to be caused or amplified by the close-range panoramic image geometry. The intensity gradient in the along-track direction can for example be related to the angular component of the panoramic images.

Data integration

The motivation of this research was to complement TLS data with reliable geochemical information to improve the interpretability of VOMs, and to enable a more detailed analysis of the mineralogy distribution in the outcrop than can be derived from the lidar and conventional image data alone. The case studies particularly at the Pozalagua quarry and the Garley canyon demonstrate that the classification of the VOMs using hyperspectral image products can significantly enhance the analysis of outcrops. In the Pozalagua quarry, different limestone and dolomite units with slightly different geochemical properties were mapped. At Garley canyon, clay and carbonate abundances were determined, to quantify carbonate concretions and to differentiate sandstone and siltstone in a shallow marine, shoreface succession.

When this project started in 2006, lightweight hyperspectral imagers with a SWIR spectral range were not available. The HySpex SWIR-320m used in this project was the first exemplar of this kind of imager provided by *Norsk Elektro Optikk AS*. When the first test dataset was collected in November 2007 in Manystones Quarry (UK) the chip-electronics were erroneous which resulted in a high noise level. Spectral classifications were therefore strongly affected by image noise. Additionally, the Spectralon calibration panels were not available at this time for atmospheric correction. Consequently, the Manystones data set was primarily utilised to develop the photogrammetric data integration. The chip-electronic was exchanged before the other data sets were acquired.

The data integration was performed using a cylindrical camera model including additional correction parameters, as proposed by Schneider and Maas (2006). This model matches best the image acquisition and geometric characteristics of the HySpex imager. The registration of the spectral imagery in the lidar coordinate system as well as the texturing of the 3D lidar models with the hyperspectral classifications and image products could be achieved with a precision of around one image pixel (equating to 2.3-7.5 cm for images with scanning ranges between 30-100 m). According to natural heterogeneities in geological systems, this range of uncertainty is acceptable for most geological applications.

The benefit of the data integration has been discussed in Paper 1. While the improved interpretability of VOMs and the possibility to quantify lithological units in an outcrop has been demonstrated, other advantages are not shown in this study. Nevertheless, the photogrammetrically correct data integration is the essential pre-condition to utilize the geometry derived from the lidar data to improve the nonuniformity and spectral image correction in future research.

A common result of hyperspectral mapping is that multiple image products are generated, either because different classification approaches are used to enhance the confidence level, or because the classification method produces multiple output images. Spectral unmixing methods for example generate one abundance image for each spectral end-member. Consequently, for efficient interpretation it is desirable to visualise multiple spectral products as superimposed layers in the VOMs. Multitexturing was therefore applied, which allowed the visualisation of multiple surfaces with different textures in the lidar model. Multitexturing was implemented in the in-house visualisation software by S. Buckley. In many geological and remote sensing applications GIS systems are commonly used which allow the integration of different 2D image and mapping products with a large number of different layers. In contrast, as multitexturing is demanding on graphics hardware, multitexturing is currently limited in the number of layers that can be used. Furthermore, texturing is often performed with a reduced image resolution to ensure VOMs with reasonable data size. To overcome these technical problems, detailed image interpretation has been primarily performed on the 2D hyperspectral image products. However, to visualise spectral unmixing results in the VOMs, the end-member abundances images were combined to a single classification image by presenting only pixels with high abundances.

Outlook

Further research is required to improve the practicability and reliability of close-range imaging spectrometry and to solve problems recognised during this study. Particularly, the pre-processing chain needs adjustment to the close-range scanning geometry, since image corrections significantly influence the accuracy and reliability of the final spectral classification and mapping results. Future studies should be related to the following main topics:

• *Extending the collected spectral range.* In this study the spectral analysis was restricted to SWIR light. A number of geological materials, for example minerals containing transition metals such as Cu, Ni, Co, Mn, Cr, Ti and particularly Fe, show diagnostic absorption properties mainly in the VNIR light. Other minerals such as quartz and feldspar offer absorption features only within the thermal infrared spectral range. It is therefore the logical next step to extend the spectral measurement. However, because of technical reasons no lightweight hyperspectral imager is currently available which is able to measure the entire spectral range. To cover the VNIR, SWIR, and TIR spectral range, different instruments are required which result in additional processing to integrate scenes from multiple sensors.

• *Image non-uniformity correction*. Additional research is required to get a better understanding of the image artefacts which frequently appear in close-range hyperspectral imagery. Nonuniformity correction needs to be adjusted to the close-range and panoramic scanning geometry by utilising geometric parameters retrieved from the lidar data.

• *Reflectance*. More sophisticated spectral correction needs to be implemented in the processing workflow to extract more accurate reflectance quantities. A number of topographic correction methods have been developed for nadir imagery such as the C, Gamma or Minnaert normalization (Richter et al. 2009). Future studies need to evaluate in what way these methods can be adopted or modified for the close-range case. The solar illumination and viewing geometry can be derived from the lidar data. Particularly shadow correction needs to be implemented in future studies.

To overcome the problems related to the EL correction, it would be desirable to extract reflectance quantities by radiative transfer modelling. In close-range scanning, data on the local atmosphere, and optical depth could be collected without additional logistical cost. Processing is usually performed by using look-up tables to provide correction coefficients for different scanning conditions. However, commercial correction packages currently available such as FLAASH (implemented in ENVI) do not provide correction coefficients for close- range scanning conditions. Additional research is required to utilise radiative transfer models for the spectral correction of close-range spectral images.

• *Enhanced photogrammetric possessing*. In this study, the correspondence between the spectral imagery and the lidar data have been established by manually measured CPs. The manual collection of CPs can be time consuming and erroneous. Methods such as image matching are required to establish the data correspondence in an automated and robust manner from data with disparate resolutions.

The photogrammetric performance of the HySpex imager has been examined in an empirical rather than analytical manner. If higher photogrammetric accuracy is desired, the camera calibration needs to be performed in a photogrammetric measuring field optimised to the HySpex imager. Additionally, the photogrammetric camera model may need to be adjusted to the requirements of the HySpex imager for highest accuracy.

• *New visualisation concepts*. Multitexturing of VOMs significantly improved the visualisation of multiple hyperspectral image products. Beside progress in hardware technology, visualisation may also be improved by more sophisticated processing. The visualisation of multiple image products in a 3D environment could benefit from new concepts and strategies in computer graphics. Visualisation concepts from other branches such as volume rendering used in medical applications might give inspiration to solve problems associated with the multitexturing of 3D models.

The results of this research illustrate the potential of close-range hyperspectral imaging for a number of applications where the study of mineral-chemical composition is essential, for example in mining, building damage assessment, archaeology and culture heritage studies, or in forestry assessment for canopy analysis. With an increased availability of lightweight hyperspectral imagers, this remote sensing branch will see an increased focus of research in the coming years. Research focuses needs to be related to nonuniformity, atmospheric and adjacency corrections methods adjusted to the specific requirements of the close-range scanning geometry. It can be hoped that close-range imaging spectrometry will become a sub-discipline in remote sensing, and a standard tool in field-based geoscience studies.

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